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WELDING RESEARCH

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ASSOCIATION NOTES

Resignation of Assistant Director

At their meeting on 30 January the Council learned with regret that Dr. Nicol Gross, who had been with the Association since 1945, had tendered his resignation. On the motion of the President, Sir William J. Larke, K.B.E., seconded by the Chairman, Sir Charles S. Lillicrap, K.C.B., and supported by the members of Council, the following resolution was passed:

> "That this Council with deep regret accept the resignation of Dr. Gross on his appointment to an important position in South Africa. The Council desire to place on record their high appreciation of the great contribution which Dr. Gross has made to the rapid and progressive development of the work and equipment of the Research Station; their gratitude for his outstanding contribution to welding research during the past six years, and for his contribution to the work of the Association generally, by reason of his rare combination of high attainments as a scientist, with those of an able administrator with high capacity for leadership. This Council extend to him their warmest congratulations and good wishes for his success in his new appointment."

Membership

Since the report in the October, 1951, issue of the Journal, the following companies have joined the Association:

B.I.P. Engineering Ltd.
Brush Aboe Group Services Ltd.
Costain-John Brown Ltd.
R. & J. Dempster Ltd.
Foster Transformers & Switchgear Ltd.
Foster, Yates & Thom Ltd.
Hotpoint Electrical Appliances Co. Ltd.
Rover Co. Ltd.
St. George's Engineering Ltd.
Scammell Lorries Ltd.
Short Brothers & Harland Ltd.
Vosper Ltd.

Annual General Meeting

The Seventh Annual General Meeting of the Association, will be held at the Research Station, Abington Hall, near Cambridge, on Monday, 23 June, at 12 o'clock.

Fatigue Testing Facilities

The photograph reproduced on this page shows the north side of the recently completed Fatigue Testing Laboratory at the Engineering Research Station, Abington.

The building houses the new Losenhausen Fatigue Testing Machine, capable of 200 tons static load and 100 tons fluctuating load at speeds up to 600 cycles per minute, and other equipment including a 50-ton Denison Universal Testing Machine.

New Fatigue Testing Laboratory

R.79

CORRELATION OF WELDABILITY TESTS WITH STRUCTURAL JOINTS

Part II—Investigations with Unrestrained Fillet Tests and Structural Joints

This is the second of three reports on an investigation undertaken by the British Welding Research Association to produce a test for hard-zone cracking in arc-welded low alloy steel. Part I was published in the February, 1952, issue of this journal.

By C. L. M. COTTRELL, M.Sc., and M. D. JACKSON, B.Met., A.I.M.

SYNOPSIS

The relative effects of joint rigidity and rate of cooling on the initiation of hard-zone cracking have been studied in an attempt to resolve the two effects, and to provide a scientific basis for the correlation of weldability tests and structural joints. The effect of the potential hydrogen content in the electrode coating on the incidence of hard-zone cracking has also been studied.

It has been shown that the rate of cooling at 300 deg. C. in the heat-affected zone adjacent to the fusion line can be used as a criterion of weldability. When a critical rate of cooling is exceeded, hard-zone cracking is liable to occur.

The existence of a constant critical cooling rate in all tests, irrespective of the external restraint imposed, implies that the effect of restraint is a minor one in the initiation of cracking. However, it has been observed previously that the full size Reeve weldability test is more severe than the corresponding miniature Reeve test. The reason for this difference becomes apparent when cooling rate is taken as an indication of severity.

A new test is proposed which gives special conditions of heat flow. This test has a greater severity than the existing miniature Reeve test, which makes it more comparable with the severity of structural joints.

INTRODUCTION

This investigation was undertaken to determine the conditions for making sound welds in structures fabricated from a low alloy manganese-molybdenum steel having a yield strength (0·3 per cent. proof stress) of 27 tons per sq. in.

The most common type of welded-joint failure in alloy steels is the formation of cracks in the hardened zone of the plate immediately adjacent to the fusion line. It has been suggested by Hopkin[1] that hydrogen which is dissolved in the weld metal is a contributory cause of hard-zone cracking. The relative effects of joint rigidity and rate of cooling on the initiation of hard-zone cracking have not, up to the present, been fully understood. The most satisfactory weldability test now in use incorporates maximum restraint combined with fast rates of cooling. This test is known as the Reeve[2] fillet weld cracking test. The inability to differentiate between effects of the two factors, joint rigidity and cooling rate has been a serious difficulty in attempting to modify the Reeve test. Until recently the general view has been that it would be safer to retain test conditions more severe than those found in practice, rather than to accept a test that would classify as weldable a steel which might be difficult to fabricate.

The tests available at the start of this investigation were the Reeve, modified Reeve[2] and miniature Reeve tests. Modifications have been made to these tests with the object of obtaining a simple weldability test with equivalent conditions of severity to those in a given structural joint. These modified tests and their results were described in Part I[4]. The results indicated that further work was necessary to determine the relative effects of rate of cooling and restraint and to devise a simple and reliable weldability test. This further work is described here.

MATERIALS USED IN THE TESTS

Table I gives the analyses of the various casts of manganese-molybdenum steel used in the tests, and also the carbon equivalent of each cast.[3]

The electrodes for all tests were baked at 110 deg. C. for a minimum period of one hour immediately before use. This treatment was carried out to ensure that the moisture content (potential hydrogen) of each type of electrode coating was maintained at a constant low value.

Table II

B.E.A.M.A.-I.O.W. Classification	Type of Coating	Sizes of Electrode Used
E.217	Rutile	10, 8, 6 and 4 s.w.g.
E.317	Rutile basic	10, 8, 6 and 4 s.w.g.
E.645	Lime (low hydrogen)	6 s.w.g., $\frac{1}{4}$ in.

UNRESTRAINED WELDABILITY TESTS

(a) Unrestrained Fillet Water-bath Test

In this test, water was used as a means of extending the effective heat-sink of small plates. A fillet weld was made

Table I.—Cast Analyses

Section	C %	Si %	S %	P %	Mn %	Ni %	Cr %	Mo %	Cu %	Carbon Equivalent*
6 in. × 3 in. channel	0·19	0·23	0·016	0·015	1·28	0·36	0·16	0·26	—	0·52
6 in. × 3 in. bar and 3 in. × 1½ in. joists	0·17	0·08	0·031	0·020	1·34	0·49	0·11	0·25	0·17	0·51
3 in. × 1½ in. joists	0·21	0·15	0·025	0·018	1·49	0·33	0·07	0·27	—	0·56
¾ in. plate	0·16	0·15	0·019	0·023	1·27	0·37	0·15	0·24	—	0·49
½ in. plate	0·18	0·16	0·043	0·037	1·26	0·47	0·10	0·26	—	0·51
1 in plate	0·18	0·16	0·027	0·024	1·24	0·55	0·195	0·26	—	0·53

* The sizes of electrodes used for the tests are given in Table II with their B.E.A.M.A.-I.O.W. coating classification.

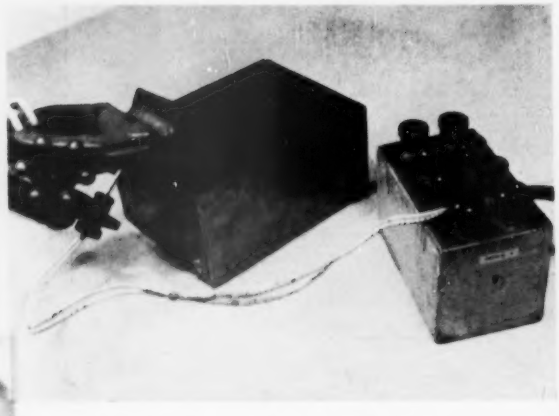


Fig. 1. View of unrestrained fillet water bath test showing thermocouple attachment.

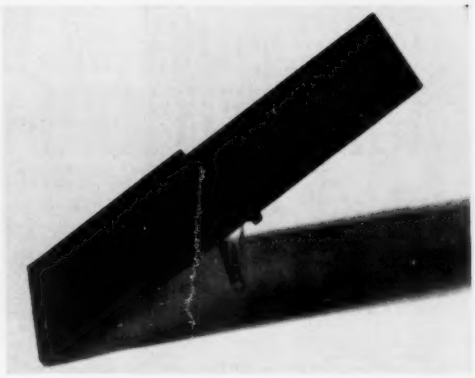


Fig. 2. View of unrestrained fillet test.

between two 1 in. thick plates of manganese-molybdenum steel. The two plates were supported at an angle of 45 deg. to the horizontal on a block of steel in a copper tank which was partially filled with water, as shown in Fig. 1. The volume of water in the tank was 2,500 ml. and the surface of the water was approximately 1½ in. below the root of the fillet weld. The bottom plate projected 1 in. beyond the edge of the top plate and the test fillet weld was made in the downhand position. The water was at room temperature immediately before welding.

(b) Unrestrained Fillet Test

This test consisted of a test fillet weld made between a top and bottom plate of ¼ in. thick manganese-molybdenum steel as shown in Fig. 2. The dimensions of the top and bottom plates were 6 in. by 4 in. and 12 in. by 4 in. respectively. These lengths of plate were chosen in order to obtain a sufficiently large heat-sink to avoid heat saturation during welding. At the same time heat-flow away from the weld was restricted by the small plate thickness.

Two different degrees of thermal severity were obtained with the unrestrained fillet test. The less severe test weld (bithermal)* was made at the end of both plates as shown in Fig. 3 (*a*). The more severe test with trithermal* severity is shown in Fig. 3 (*b*) and the test weld was made between the end of the top plate and the middle of the bottom plate. The test weld length in the bithermal test was 3 in., but in the trithermal test, weld lengths of 4, 3 and 2 in. were used. These variations of weld length were made to study the effect of "weld length/plate width" ratio on cooling rate and hard-zone cracking. In all instances the mid-point of the weld coincided with the centre-line of the plates.

The trithermal test assembly was used to test plates in various conditions.

(i) As-rolled (cut from 6 in. by 3 in. channel sections).
(ii) As-rolled (cut from plate).
(iii) Normalised, scale remaining (cut from channel).
(iv) Normalised and machined (cut from channel).

The normalising treatment was carried out by soaking the plates at 900 deg. C. for twenty minutes and cooling in still

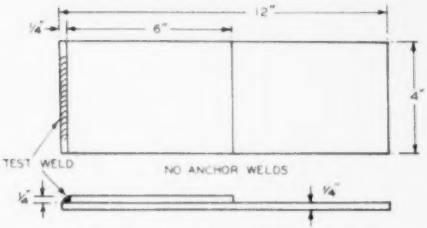


Fig. 3(a). The B.W.R.A. unrestrained fillet test (*bithermal severity*).

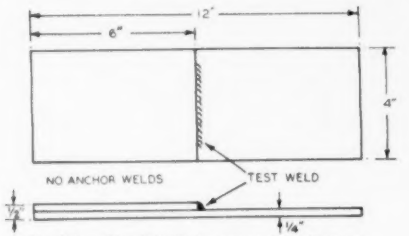


Fig. 3(b). The B.W.R.A. unrestrained fillet test (*trithermal severity*).

air. These additional tests were made to determine the effect of heat treatment and surface condition on weldability.

The plates for both bithermal and trithermal tests were supported in asbestos-lined clamps at an angle of 45 deg. to the horizontal, so that the test welds were made in the downhand position.

(c) Determination of Cooling Rates

The direct cooling curves described in Part I[4], were plotted by using a strip-chart recorder with a recording speed of one dot every five seconds, and it was realised that the method was not suitable where fast rates of cooling (more than 5 deg. C. per sec.) were obtained. This necessitated a recording method with a much faster response, and to satisfy this requirement a photographic recording apparatus was constructed.

The apparatus consisted of a fast response (0·3 sec.) temperature indicator calibrated to read in centigrade degrees

* A test with bithermal severity is one in which heat can flow away from the weld through two plate sections; similarly in a test with trithermal severity heat can flow through three plate sections.

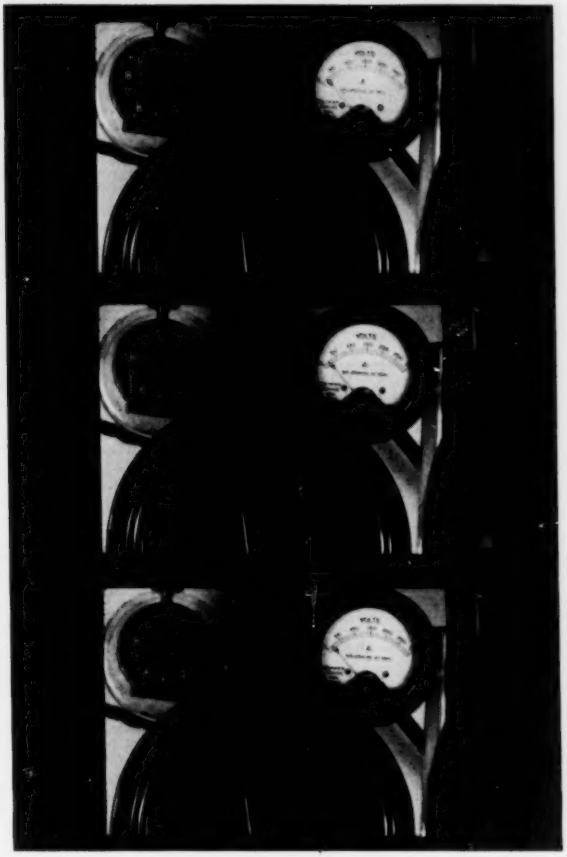


Fig. 4. Film record.

a 1/20th second stop watch and an arc-voltage indicator, all three instruments being photographed continuously on 16 mm. film during and after welding. For this purpose an R.A.F. gun-camera was modified to work at a rate of two exposures per second. A typical film record of three consecutive frames is shown in Fig. 4. It will be observed that the important instruments had black dials with white markings to facilitate reading the film negative.

The fast-response temperature indicator was connected to the thermocouple via an external balancing resistance and a cold junction. The balancing unit was included because the very low internal resistance of the indicator (9·7 ohm) necessitated a fixed value of resistance (6 ohm) in the external thermocouple circuit. The voltage indicator connected across the welding arc fixed the start and finish of the welding period with respect to the cooling curve.

The thermocouples consisted of 22 s.w.g. chromel and alumel wires which were fused together to form a bead. A flat was then ground on the bead to form a hemispherical shape. This bead was then flash welded to the inside of a thimble made of manganese-molybdenum steel and the thimble was driven into a reamed hole in the bottom plate, a cross-section through a typical assembly being shown in Fig. 5. The centre of the reamed hole was at the mid-point

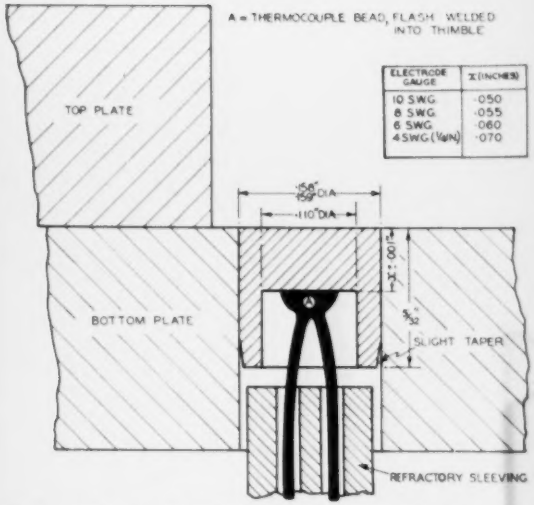


Fig. 5. Diagram showing method of insertion of thermocouple.

of each test weld and 1/8 in. to 3/16 in. from the weld root, depending upon the size of electrode being used. This ensured that the thermocouple was about halfway along the horizontal leg of the test fillet weld. The thickness of the top of the thimble was varied according to the size of electrode being used, as indicated in Fig. 5, to ensure that the thermocouple tip was just inside the heat-affected zone, where peak temperatures of about 1,200 deg. C. occur. This procedure for attaching the thermocouple was used for the majority of the test welds. However, in the four experiments with the unrestrained fillet water-bath test the thermocouple tip was pressed against the end of a blind hole drilled in the bottom plate, as described in Part I[4].

The films were read using a film strip projector fitted with a 25 mm. lens, and direct cooling curves were plotted on linear graph paper from the results. Rates of cooling at various temperatures were obtained by taking tangents from the direct curves.

(d) Welding Conditions

Alternating current with an open-circuit voltage of 80 volts was used for all the tests. The welding current was measured by means of a current transformer and moving-iron ammeter, and the arc energy was recorded with an induction-type integrating watt-hour meter.

All welds were made in the downhand position with the plates at room temperature, using Class E.217 electrodes; the welding conditions are given in Table III. Four test welds having different fillet sizes were deposited using the water-bath assembly. Two test welds of different fillet sizes were made with both bithermal and trithermal unrestrained assemblies, and some extra tests with different weld lengths and plate conditions were made with the trithermal assembly

(e) Examination of Test Welds

The test assemblies were left for a week before sectioning, and the test welds were cut out parallel to the welding direction with a power hack-saw. Three cross-sections were then taken from each weld.

The sections were micro-polished, etched in a solution of 3 per cent. hydrochloric acid with 3 per cent. picric acid in alcohol and examined microscopically for cracks.

Table III.

Welding Conditions. Manganese-Molybdenum Steel: Electrodes Class E.217

Test Assembly	Plate Thickness (Inches)	Plate Condition	Electrode Size (s.w.g.)	Weld Length (Inches)	Welding Current (Amps.)	Energy Input (Joules/in. × 10-3)	Fillet Size (Inches)
Unrestrained fillet water-bath	1	Normalised and machined	10	2½	125	20	3/16
			8	2½	173	30	¼
			6	2½	212	41	5/16
			4	2½	305	66	7/16
Unrestrained fillet trithermal	¼	From channel section as rolled	10	2	130	21·2	3/16
			10	3	133	19·6	3/16
			10	4	133	19·9	3/16
			8	3	180	27·5	¼
		Plate as rolled	10	2	133	19·7	3/16
			10	3	130	20·6	3/16
			10	4	130	22·0	3/16
		Normalised	10	3	130	22·8	3/16
		Normalised and machined	10	3	135	21·6	3/16
Unrestrained fillet bithermal	¼	As rolled	10	3½	130	18·3	3/16
			8	3	169	32·0	¼

Crack lengths were measured on the screen of a projection microscope, adjusted to give an accurate magnification of 250 diameters, and their lengths were recorded as a percentage of the total leg-length.

Hardness surveys were made with a diamond pyramid indenter and 10 kg. load on the centre section from each test weld.

(f) Results

The tests using the unrestrained fillet water-bath assembly with 1 in. thick steel all showed cracking in the hard zone. This result is important since it was previously thought that external restraint was the major factor in the formation of hard-zone cracks. The results for the tests made with the 10 and 4 s.w.g. electrodes are given in Table IV, and those for the 6 and 8 s.w.g. electrodes are mentioned for completeness, though these tests were not fully examined.

Table IV. Results obtained with the Unrestrained Fillet Water-bath Test. 1 in. thick Manganese-Molybdenum Steel. Electrodes Class E.217

Fillet Size (In.)	Energy Input (Joules/in. × 10-3)	Hardness Values (D.P.N. 10 kg. load)		Hard-Zone Cracking of Leg-Length (Per Cent.)
		Average Peak Hard Zone	Average Weld Metal	
3/16	20	439	306	28
¼	30	—	—	Cracked
5/16	41	—	—	Cracked
7/16	66	382	239	9

It can be seen from Table IV that the cracking is quite severe with the weld of smallest fillet size and less severe with the largest weld. This result is to be expected if rate of cooling in the hard zone is a major factor in the formation of hard-zone cracks. Another interesting feature is the presence of cracking with an average peak hardness value in the hard zone of only 382 D.P.N., because joint rigidity cannot be responsible for this cracking.

Square-root cooling-rate curves for the water-bath tests are shown in Fig. 6, and the fact that these curves deviate only slightly from straight lines indicates that the water-bath provided a sufficient heat-sink to avoid heat-saturation of the test plates.

The results obtained with the unrestrained fillet test on ¼ in. thick steel have shown that, as with the water-bath test, hard-zone cracks can be obtained in unrestrained fillet welds.

The effect of test weld length on hard-zone crack formation and cooling rate was studied. Decreasing the test weld length from 4 in. to 3 in. yielded both an increase in hard-zone cracking and in cooling rate, and this effect is shown in Table V and Fig. 7. However, decreasing the test weld length from 3 in. to 2 in. has not produced such a marked change.

Table V.—Effect of Test Weld Length on Hardness and Cracking in Hard Zone. Trithermal Unrestrained Fillet Test. Manganese-Molybdenum Steel, As Rolled ¼ in. Thick. Fillet Size 3/16 in., 10 s.w.g. Electrodes Class E.217

Steel Origin	Test Weld Length (Ins.)	Energy Input (Joules/in. × 10-3)	Hardness Values (D.P.N. 10 kg. load)		Hard-Zone Cracking (Per Cent. Leg Length)
			Average Peak Hard Zone	Average Weld Metal	
From 6 × 3 in. channel web	2	21·2	412	252	10
	3	19·6	415	228	12
	4	19·9	398	227	Nil
From ¼ in. plate	2	19·7	403	243	12
	3	20·6	386	235	7
	4	22·0	370	244	Nil

It will be seen in Table V that the two casts of steel, one in the form of plate and the other in channel section, gave different degrees of hardening in the heat-affected zone for similar welding conditions. This difference in hardenability appeared to have little effect on weldability, whereas the different cooling rates over the whole temperature range, as shown in Fig. 7 for one cast, had a much greater effect on weldability. This result again emphasises the marked effect of cooling rate on the initiation of hard-zone cracks.

Similar test welds made on the unrestrained fillet assembly with variations in joint geometry have given some interesting results. The trithermal test assembly has proved more severe than the bithermal test assembly both from the point of view of hard-zone cracking and rate of cooling. The difference in cooling rate for the two test assemblies is shown in Fig. 8, which also shows that a ¼ in. fillet weld (8 s.w.g. electrode)

made on the trithermal assembly gives similar cooling rates to a 3/16 in. fillet weld (10 s.w.g. electrode) on the bithermal assembly. The difference between cooling rates for similar welds on the two assemblies shows the difference in heat flow between butt welds and fillet welds as represented by the bithermal and trithermal tests respectively.

The effect of joint geometry on hard-zone cracking is shown in Table VI where results are given for bithermal and trithermal tests on $\frac{1}{4}$ in. thick plate. Table VI also gives hardness values for the hard zone of both bithermal and trithermal tests, the hardness being greater with the trithermal test.

Table VI.—Effect of Joint Geometry on Hard-Zone Cracking and Hardness. Unrestrained Fillet Test. $\frac{1}{4}$ in. Steel Plates. 10 s.w.g. Electrodes Class E.217. Weld Length 3 in.

Test	Energy Input (Joules/in. $\times 10^{-3}$)	Hardness Values (D.P.N. 10 kg. load)		Hard-Zone Cracking (Per Cent. Leg Length)
		Average Peak Hard Zone	Average Weld Metal	
Bithermal ..	18·3	358	218	Nil
Trithermal ..	20·6	386	235	7

Test welds have been made with the trithermal unrestrained fillet-weld assembly on the steel in different conditions. The plates were as-rolled, normalised, and normalised with subsequent machining, giving three different surfaces on which test welds were made. There was some indication that the unmachined normalised plate gave the best weldability as shown in Table VII, although the tests are not exactly comparable, owing to small variations in heat input. It is possible that large amounts of iron oxide in the weld pool, due to the relatively thick normalising scale, may have affected the oxygen/hydrogen equilibrium. If so, then the reduction of potential hydrogen would tend to lessen the severity of hard-zone cracking.

Table VII.—Effect of Plate Surface Condition on Weldability. Steel Manganese-Molybdenum $\frac{1}{4}$ in. Plates. Electrodes 10 S.W.G., Class E. 217, Fillet size $\frac{3}{16}$ in. Weld length 3 in. Trithermal Unrestrained Fillet Test.

Plate Surface Condition	Energy Input (Joules/in. $\times 10^{-3}$)	Hardness Values (D.P.N. 10 kg. load)			Hard-Zone Cracking (Per Cent. Leg Length)
		Average Peak Hard Zone	Average Weld Metal	Average Plate	
As-rolled	20·6	386	235	227	7
Normalised	22·8	381	224	191	Nil
Normalised and Machined	21·6	386	232	194	3

Normalising treatment alone does not appear to affect weldability. Normalising the steel effected a reduction in initial plate hardness, but did not result in a corresponding reduction in hardness in the heat-affected zone.

The cracks found in the unrestrained fillet tests were visible only at magnifications of over 100 diameters and have been termed micro-cracks.

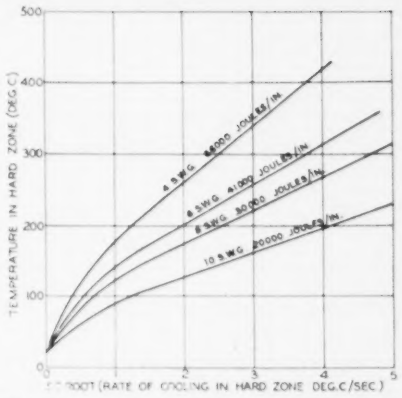

TEMPERATURE IN HARD ZONE (DEG.C)
SQ. ROOT (RATE OF COOLING IN HARD ZONE DEG.C/SEC)
4 S.W.G. 48000 JOULES/IN.
6 S.W.G. 41000 JOULES/IN.
8 S.W.G. 30000 JOULES/IN.
10 S.W.G. 20000 JOULES/IN.

Fig. 6. Square-root cooling-rate curves. Unrestrained fillet water-bath test with 1 in. plates.

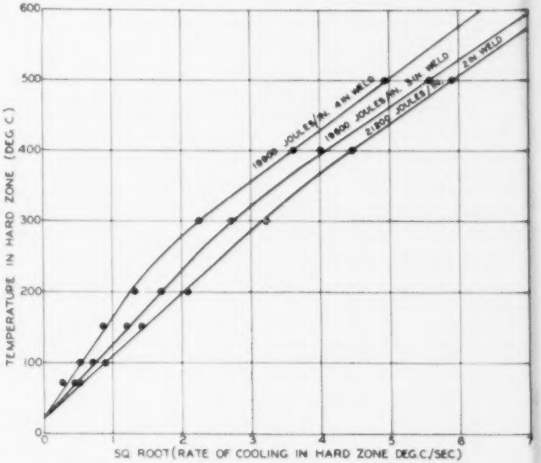


Fig. 7. Square-root cooling-rate curves for trithermal unrestrained fillet test in $\frac{1}{4}$ in. material, showing effect of test weld length.

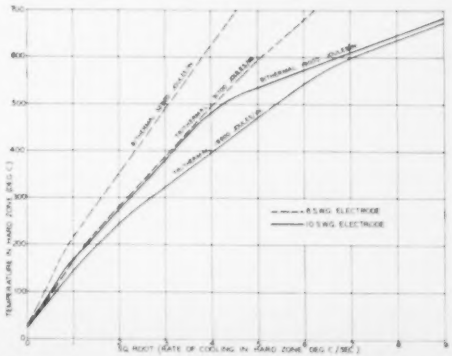


Fig. 8. Square-root cooling-rate curves. Unrestrained fillet tests of bithermal and trithermal severity in $\frac{1}{4}$ in. plates.

TESTS ON STRUCTURAL JOINTS

(a) Joint Dimensions

The structural tests consisted of welds made on channel section, I-section, and plate of various thicknesses. Three of the joints were made between manganese-molybdenum steel members, and one other joint was made between alloy and mild steel. The joints tested, with their code letters and dimensions, are shown in cross-section in Figs. 9, 10, 11 and 12.

(b) Test Details

The welding procedure and cooling curve determinations were similar to those used for the unrestrained fillet tests, and are described in the earlier sections of this report. Three types of electrode were used in these tests: class E.645 electrodes were used with an open-circuit voltage of 100 volts, instead of 80 volts, as used for the other two electrodes (E.217 and E.317).

The welding conditions for the tests are given in Table VIII. Test welds on joints A and C were made in the horizontal position. The deposition ratio for the test welds on joints A and B was $1\frac{1}{2}$ in. electrode per inch of weld, whereas for joints C and J the ratio was increased to 2 in. and 3 in. respectively.

The joints were incorporated in a rigid structure to ensure the presence of external restraint.

(c) Results

The form of the square-root cooling-rate curves for the various joints tested is modified by the heat sink saturation and by other effects such as cessation of heat input at the finish of welding. Curves for joints A and B (Fig. 13) show changes of slope at various temperatures. In cooling through the temperature range 400-300 deg. C. the slopes of the curves for joint A become less steep, this change coinciding with the heat-saturation of the top flange of the I-beam. A similar effect is shown in joint B, though this occurs at a lower temperature (300-200 deg. C.) and is probably due to the effect of the hole in the $1\frac{1}{2}$ in. thick bar. The change to a steeper slope in the 500-400 deg. C. region with joint B is the reverse effect to that produced by the saturation of a heat-sink. This reverse effect is probably due to the finish of welding at a point where an abrupt change in heat distribution occurs.

Comparison of the square-root cooling-rate curves for joints A and B shows that similar cooling-rates can be obtained over the temperature range 400-250 deg. C. by adjustment of both heat input and joint geometry.

Square-root cooling-rate curves for joints C and J are given in Fig. 14, from which it will be seen that joint J gives a straight line. This indicates that the heat-sink is infinite with respect to heat input and the curve therefore agrees with Rosenthal's equation[4, 5]. In joint C the slope of the curves increases slightly on cooling through the temperature range 600-400 deg. C. and this again is probably due to the cessation of welding.

The results of these tests on structural joints indicate that the extent of hard-zone cracking depends on the type of electrode used. These results are given in Table IX and values for hardness developed in the hard zone are also shown for comparison. It has been shown that the low-hydrogen electrode from class E.645 is less liable to cause cracking in the manganese-molybdenum steel than the electrodes of class E.217 and E.317 tested. There is also some indication that the class E.317 electrode is better than the E.217 electrode.

SUMMARY OF RESULTS WITH RESTRAINED, UNRESTRAINED AND STRUCTURAL TESTS

(a) Correlation of Cooling Rates and Hard-Zone Cracking

Since it appeared from the results previously obtained that rate of cooling in the hard zone was an important factor in the initiation of hard-zone cracks, it was decided to investigate the effect of rate of cooling at various temperatures on hard-zone crack formation.

In order to relate cooling rate at various temperatures in the heat-affected zone with cracking in that zone, it was necessary to observe two cooling-rate curves in each test. One curve was from a test in which slight cracking had occurred, the other from a test with slightly lower cooling rate, but in which no cracking had occurred. The area formed between these two curves indicated a borderline region of weldability. Several pairs of curves, taken from various weldability tests and structural joints, were plotted together, and the area of doubtful weldability was thus limited to a given range of temperature.

Several pairs of these curves for tests with E.217 electrodes on the alloy steel are shown in Fig. 15, and the area of doubtful weldability is shown hatched. Although the external restraint imposed on these test welds varied from severe to no restraint, there is a range of temperature over which rate of cooling in the hard zone appears to have a major influence in the initiation of hard-zone cracks. This range of temperature extends from about 200 to 400 deg. C.

It is considered that there is some theoretical basis for the importance of the temperature range 200-400 deg. C. since

Table VIII. Welding Conditions for Structural Joints

Joint Code	Members Joined	Electrode		Weld Length (Inches)	Welding Current (Amps.)	Energy Input (Joules in. $\times 10^{-3}$)	Fillet Size (Inches)
		Class	Size (s.w.g.)				
A	3 in. × $1\frac{1}{2}$ in. I beam to $\frac{3}{4}$ in. plate (M.S.)	E.217	10	3	132	19	$\frac{3}{16}$
		E.217	8	3	179	29	$\frac{1}{4}$
		E.317	10	3	131	19	$\frac{3}{16}$
		E.317	8	3	175	33	$\frac{1}{4}$
B	6 in. × 3 in. channel to $1\frac{1}{2}$ in. thick bar	E.645	6	5	201	39	$\frac{5}{16}$
		E.645	($\frac{1}{4}$ in.)	5	281	55	$\frac{5}{16}$
		E.217	6	5	220	42	$\frac{5}{16}$
		E.317	6	5	221	40	$\frac{5}{16}$
C	6 in. × 3 in. channel to 3 in. thick bar	E.645	($\frac{1}{4}$ in.)	5	300	80	$\frac{1}{4} \times \frac{1}{2}$
		E.645	($\frac{1}{4}$ in.)	5	270	114	$\frac{1}{4} \times \frac{1}{2}$
		E.217	4	5	307	79	$\frac{1}{4} \times \frac{1}{2}$
		E.217	4	5	295	110	$\frac{1}{4} \times \frac{1}{2}$
J	6 in. × 3 in. channel to 3 in. thick bar	E.645	($\frac{1}{4}$ in.)	7	302	80	$\frac{1}{2}$
		E.217	4	7	317	85	$\frac{1}{2}$
		E.317	4	7	321	74	$\frac{1}{2}$

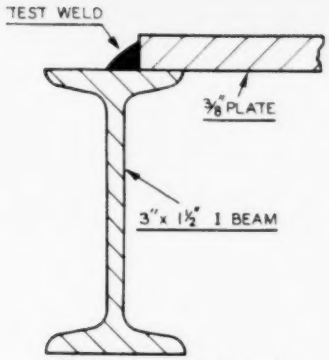


Fig. 9. Section through joint A.

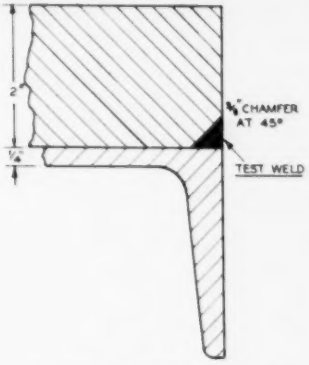


Fig. 12. Section through joint J.

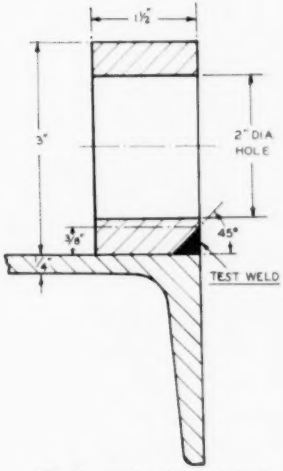


Fig. 10. Section through joint B.

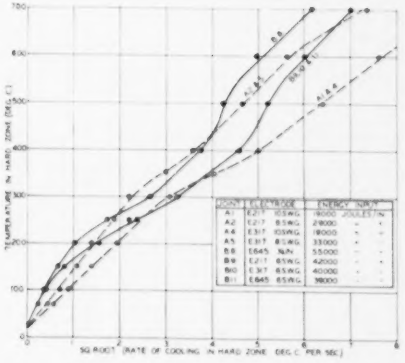

TEMPERATURE IN HARD ZONE (DEG C)
SQ ROOT (RATE OF COOLING IN HARD ZONE DEG C PER SEC)
JOINT ELECTRODE ENERGY INPUT
A1 E7-7 05 WG 19000 JOULES/IN
A2 E7-7 05 WG 29000 " "
A4 E7-7 05 WG 19000 " "
A5 E7-7 05 WG 33000 " "
B8 E 645 3/16 IN 55000 " "
B9 E7-7 05 WG 42500 " "
B10 E7-7 05 WG 40000 " "
B11 E 645 05 WG 58000 " "

Fig. 13. Square-root cooling-rate curves for structural joints. (A. and B.)

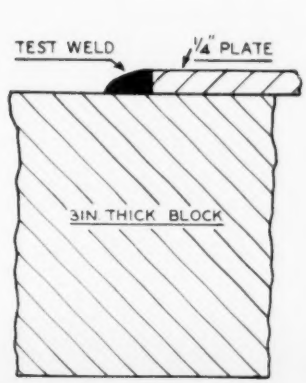


Fig. 11. Section through joint C.

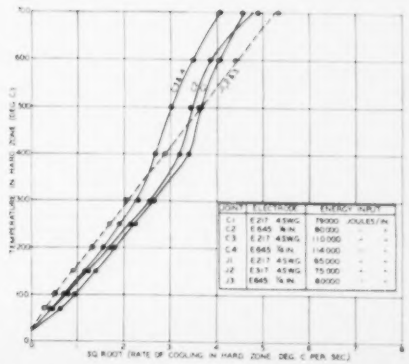

TEMPERATURE IN HARD ZONE (DEG C)
SQ ROOT (RATE OF COOLING IN HARD ZONE DEG C PER SEC)
JOINT ELECTRODE ENERGY INPUT
C1 E7-7 45 WG 78000 JOULES/IN
C2 E 645 3/16 IN 80000 " "
C3 E7-7 45 WG 110000 " "
C4 E 645 3/16 IN 114000 " "
J1 E7-7 45 WG 85000 " "
J2 E3-1 45 WG 75000 " "
J3 E 645 3/16 IN 80000 " "

Fig. 14. Square-root cooling-rate curves for structural joints. (C. and J.)

Table IX. Results of Tests on Structural Joints. Manganese-Molybdenum Steel

Joint Code	Electrode Class	Fillet Size (Inches)	Energy Input (Joules/in. × 10^{-3})	Hardness Values (D.P.N. 10 kg. load)			Hard-Zone Cracking (per cent. Leg Length)
				Average Peak Hard Zone	Average Weld Metal	Average Plate	
A	E.217	5/16	19	403	245	232	3·7
	E.217	1/4	29	355	232		Nil
	E.317	5/16	19	398	233		Nil
	E.317	1/4	33	336	211		Nil
B	E.645	5/16	39	379	231	216	Nil
	E.645	1/4	55	344	217		Nil
	E.217	5/16	42	384	220		23
	E.317	5/16	40	394	213		15
C	E.645	1/2 3/8	80	348	236	204	Nil
	E.645	1/2 1/2	114	334	233		Nil
	E.217	1/2 3/8	79	377	233		1·6
	E.217	1/2 1/2	110	309	192		Nil
J	E.645	1/4	80	302	216	214	Nil
	E.217	1/4	85	305	210		Nil
	E.317	1/4	74	342	185		Nil

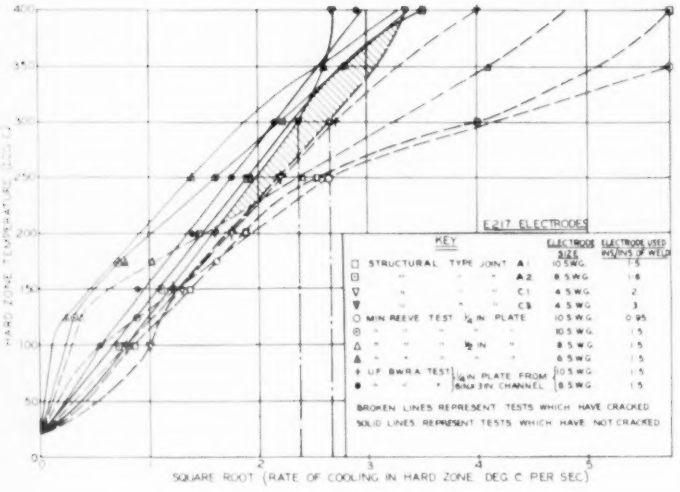


Fig. 15 (*left*). Comparison of square-root cooling-rate curves for slightly cracked and uncracked joints.

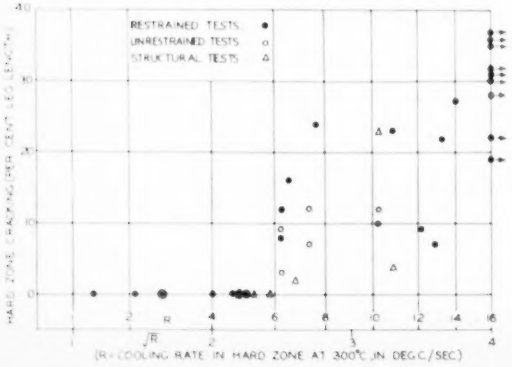

RESTRAINED TESTS
UNRESTRAINED TESTS
STRUCTURAL TESTS
HARD ZONE CRACKING (PER CENT. LEG LENGTH)
(R = COOLING RATE IN HARD ZONE AT 300°C. IN DEG.C./SEC.)

Fig. 16. Relation between hard-zone cracking and rate of cooling. Electrode class E.217.

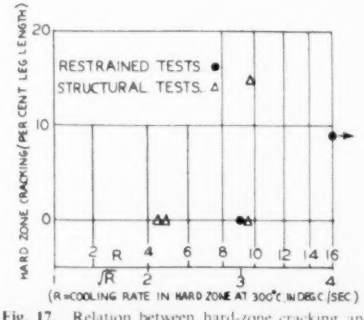


Fig. 17. Relation between hard-zone cracking and rate of cooling. Electrode class E.317.

it represents cooling during the transformation of the heat-affected zone from austenite to martensite. It is known that the plate material immediately adjacent to the fusion line becomes charged with hydrogen from the weld metal. This hydrogen will probably be forced into the plate material during the depressed transformation point (600 deg. C. approx.) of the weld metal, when there is a sudden drop in the solubility of hydrogen. If the plate material becomes charged with hydrogen in this manner (while it is still in the austenitic state), then as the metal transforms at lower temperatures (300-400 deg. C.) the hydrogen will be thrown out of solution. It is possible that the release of hydrogen in the martensite at this stage leads to the production of stress centres, which may account for the importance of cooling rate over this temperature range.

The rate of cooling at high temperatures (400-900 deg. C.) decides the transformation products to be found in the heat-affected zone, whereas the rate of cooling at low temperatures (room temperature—200 deg. C.) probably controls the progress of delayed transformation (i.e. decomposition of retained austenite). This delayed transformation is associated with the liberation of hydrogen and the consequent production of "stress-raisers." It is thought likely that, provided a certain rate of cooling at high temperatures (400-900 deg. C.) is obtained in the hard zone, the rate of cooling at 300 deg. C. is the main factor in the initiation of hard-zone cracks for a given electrode/plate combination. This particular cooling rate at high temperatures might well be that required to produce a small amount of martensite. Under normal welding conditions this rate is exceeded and the rate of cooling at 300 deg. C. becomes the operative factor. The square-root cooling-rate curve for joint C (Fig. 14) is a good indication of the way a comparatively slow cooling rate at high temperatures, combined with a rate at 300 deg. C. higher than the critical rate, promotes hard-zone cracking.

In the results given in Fig. 16 the rate of cooling at 300 deg. C. is related to the presence or absence of hard-zone cracking in the manganese-molybdenum steel, welded with class E.217 electrodes. When the rate of cooling at 300 deg. C. has not exceeded 6 deg. C. per sec., all casts of steel tested, have been welded without hard-zone cracks. If the steel is tested as-normalised, with surface scale remaining, then rates of cooling up to 7 deg. C. per sec. are permissible.

The results obtained from weldability and structural tests on the alloy steel, using class E.317 electrodes, have shown that no heat-affected-zone cracking occurs with rates of cooling up to about 9 deg. C. per sec. at 300 deg. C., this effect being shown in Fig. 17. However, the number of tests so far carried out with these electrodes is small compared with the number made with type E.217 electrodes, and therefore a slight modification to the critical rate of cooling may have to be made when the results of further tests are available.

The higher permissible rate of cooling with class E.317 electrodes, as compared with class E.217 electrodes, represents a definite advantage for the weldability of manganese-molybdenum steel. The main difference between the two electrodes is given in the B.E.A.M.A.-I.O.W. classification of electrodes. The coating of class E.217 electrodes has a high titania content and produces a viscous slag, whereas the coating of E.317 electrodes contains basic materials in addition to titania, and produces a fluid slag.

Comparatively few tests have so far been made on the manganese-molybdenum steel using low-hydrogen class E.645 electrodes; the results obtained are given in Fig. 18. With rates of cooling up to 11 deg. C. per sec. at 300 deg. C. no cracking has so far been observed in the steel using these electrodes.

From these few results it would appear that class E. 645 electrodes are better than E.317 for welding this alloy steel, but it must be emphasised that this conclusion is based on very few tests. E.217 electrodes have given the lowest critical cooling rate (i.e. greater liability to hard-zone cracking). The superiority of the low-hydrogen type of electrode is to be expected, but the reason for the difference between electrodes from class E.217 and E.317 is not yet apparent.

(b) Correlation between Cooling Rates obtained in Weldability Tests and in Structural Joints

As the rate of cooling at 300 deg. C. in the hard zone is an important factor in the initiation of hard-zone cracks, the comparison between weldability tests and structural joints is more easily made, since it is only necessary to compare cooling rates at 300 deg. C.

In Fig. 19 the trithermal and bithermal tests on unrestrained fillets are compared with the miniature Reeve test and structural joint A. Whereas the trithermal unrestrained fillet test gives a cooling rate at 300 deg. C. identical with that of the structural joint, the bithermal unrestrained fillet and the miniature Reeve tests give a much lower cooling rate.

From the previous results it is apparent that trithermal heat-flow is an important feature which should be incorporated in a weldability test, in order that the test may simulate cooling-rate conditions occurring in structural joints. The extension of the miniature Reeve test plates behind the

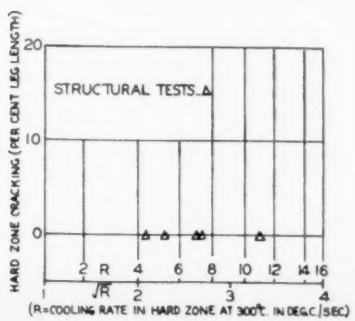

HARD ZONE CRACKING (PER CENT LEG LENGTH)
20
10
0
STRUCTURAL TESTS Δ
2 R 4 6 8 10 12 14 16
1 √R 2 3 4
(R=COOLING RATE IN HARD ZONE AT 300°C. IN DEG.C./SEC)

Fig. 18. Relation between hard-zone cracking and rate of cooling. Electrode class E.645.

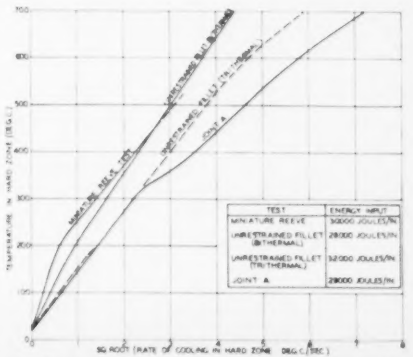


Fig. 19. Square-Root cooling-rate curves for various weldability tests and structural joint A. ½ in. steel. Electrodes 8 s.w.g. class E.217.

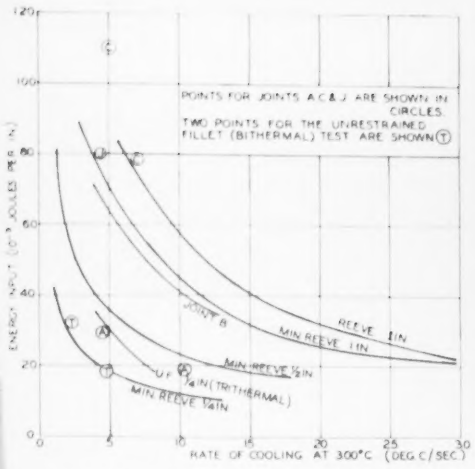
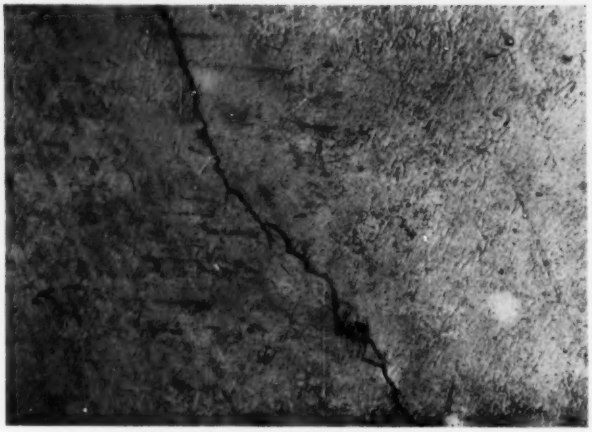

POINTS FOR JOINTS A C & J ARE SHOWN IN CIRCLES.
TWO POINTS FOR THE UNRESTRAINED FILLET (BITHERMAL) TEST ARE SHOWN (T)
JOINT B
MIN REEVE 1 IN
MIN REEVE ½ IN
MIN REEVE ¼ IN (TRITHERMAL)
MIN REEVE ¼ IN
RATE OF COOLING AT 300°C (DEG C/SEC)

Fig. 20. Relation between energy input and rate of cooling.



x100

Fig. 22. Micro-crack in hard zone of unrestricted fillet test. Etched in 2 per cent. nital.

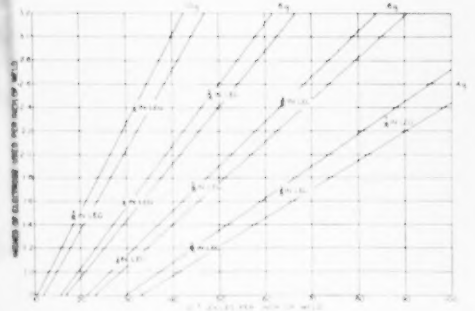
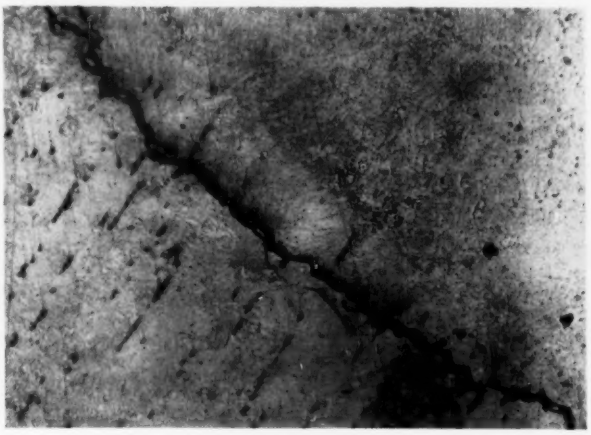


Fig. 21. Relation between energy input and electrode deposition ratio with various fillet leg-lengths. Electrode class E.217.



x100

Fig. 23. Crack enlarged due to external restraint. Modified full Reeve test. Etched in 2 per cent. nital.

test weld, as in the bithermal unrestrained fillet test, produces some increase in cooling rate at temperatures below 400 deg. C. because of the larger heat-sink, as indicated in Fig. 19. The heat flow in the sink is restricted to bithermal flow, and no increase in cooling rate is therefore obtained at high temperatures. If, however, the bottom plate is also extended in front of the test weld, the flow becomes trithermal, with consequent increase in cooling rate. When the plates are extended in this manner, test conditions can be obtained which closely resemble those occurring in structural joints.

In considering the relationship between cooling conditions in joint B and in the weldability tests, it is interesting to note that there is some tendency for the square-root cooling-rate curves to have a "hump" at about 250 deg. C., though this is much less pronounced than in the miniature Reeve test. The cause of this hump is the saturation of the heat-sink at about 250 deg. C., as the dimensions of the bar are only 5 in. by 3 in. by 1½ in., with a 2 in. dia. hole.

The tests on joints C and J have given square-root cooling conditions similar to those obtained with the full Reeve test on 1 in. plates because these joints have, in effect, infinite heat-sinks. The miniature Reeve test, however, gave square-root cooling-rate curves unlike those of the joints. The ideal test to give conditions of heat flow similar to these joints would be one having trithermal flow with an adequate heat-sink, and using 1 to 2 in. thick plates.

The relationship between energy input and rate of cooling in the heat-affected zone at 300 deg. C. is shown, for various weldability tests and joints, in Fig. 20. It will be observed that the greatest difference in cooling rate between the full Reeve and miniature Reeve tests occurs with high energy inputs, i.e. when the restriction to heat flow imposed by the two types of test is most important. Energy input can be related to fillet size as shown in Fig. 21, where the relationship is given for class E.217 electrodes.

DISCUSSION

The results of this investigation have indicated the chief factors to be taken into account in the design of a weldability test giving conditions equivalent to those obtaining in structural joints. At the start of the investigation the relative effects of external restraint and cooling rate on the initiation of hard-zone cracks were not known. It was thought that developed hardness could be related to the formation of hard-zone cracks. Although there was no doubt about the weldability of a steel which would pass the full Reeve test, it was felt that in a number of cases this test was too severe. In addition, the full Reeve test requires much preparation and material and a smaller and more simple test is therefore desirable.

These factors have been discussed both in this report and in Part I[4], and the following important points have been noted below for use in a suitable weldability test.

(*a*) External restraint is not necessary to initiate hard-zone cracks, although it assists in enlarging them.

(*b*) For a given electrode/plate-metal combination the rate of cooling at 300 deg. C. in the hard zone is a critical factor in the initiation of hard-zone cracks.

(*c*) The total heat-sink of the test assembly must be large enough for the rate of cooling at 300 deg. C. not to be affected. The heat-sink of the miniature Reeve test does not satisfy this condition, and bolting more metal to the test assembly was found to be an unsatisfactory method of adding to the heat sink.

(*d*) Where the test is to give conditions similar to a normal fillet weld it should be designed so as to incorporate conditions of trithermal flow.

Referring to point (*a*), it is desirable for some degree of external restraint to be present in a test, since this restraint tends to widen cracks which occur in the hard zone. This fact is illustrated by a comparison of Figs. 22 and 23 where Fig. 22 shows a typical micro-crack observed in the unrestrained fillet test and Fig. 23 a large crack found in the heavily-restrained full Reeve test. There is also some indication (Fig. 16) that in the fully-restrained tests the hard-zone cracks are slightly longer than in the unrestrained tests at cooling rates just above the critical value. This indicates that restraint tends to extend small cracks and so makes them more easily seen under the microscope. When faster cooling rates obtain (greater than 15 deg. C./sec. at 300 deg. C.) and cracks are longer, it appears that external restraint has little effect upon the crack length. This external restraint should not be confused with the restraint which is self-imposed by the contraction stresses due to the cooling metal, or with transformation stresses. Such contraction and transformation stresses are present in a simple "bead on plate" weld. From these considerations it would appear that some external restraint should be incorporated in the test in order to make the cracks more easily seen.

Point (*b*), which refers to the existence of a critical cooling rate, is concerned with heat-flow away from the joint, and is therefore discussed with points (*c*) and (*d*). In considering (*c*), which refers to the size of total heat-sink necessary in weldability tests, the results given in Part I[4] of this investigation are important. These results indicated that in the miniature Reeve test, cooling rates were affected by the small heat-sink as shown in Table X, which gives an additional result for $\frac{1}{4}$ in. thick plates.

It is reasonable to infer from these results that, when fillet sizes larger than $\frac{1}{4}$ in. are used, the heat-sink of the miniature Reeve test on $\frac{1}{2}$ in. plates would be inadequate (i.e. would reduce rate of cooling at 300 deg. C.). For the same test on $\frac{1}{4}$ in. thick plates fillet sizes greater than 5/32 in. would also give reduced rates of cooling at 300 deg. C. due to the saturation of the heat-sink. Since $\frac{1}{4}$ in. is the maximum size of fillet for $\frac{1}{4}$ in. material when welded in this test, it is desirable that the limiting value of 5/32 in., given previously, should be increased to $\frac{1}{4}$ in. So that the fillet size can be increased to $\frac{1}{4}$ in. without reducing the test severity, it would be necessary to enlarge the heat-sink of the miniature Reeve test considerably. The volume of the heat-sink for the new test on $\frac{1}{4}$ in. thick plates should be made not less than that of the miniature Reeve test on $\frac{1}{2}$ in. thick plates. In this test, a $\frac{1}{4}$ in. fillet (Table X) was the largest size which could be used, so that the cooling rate at 300 deg. C. was not affected. The volume of the heat-sink in the miniature Reeve test is $18\frac{1}{2}t$ cub. in., where t is the plate thickness in inches. Therefore the volume of the ideal weldability test assembly should be greater than $36\frac{1}{2}t$ cub. in.

Table X. — Temperature below which Cooling Rate is affected by the small Heat Sink in the Miniature Reeve Test. Manganese-Molybdenum Steel. Electrodes Class E.217.

Plate Thickness (In.)	Electrode Size (s.w.g.)	Fillet Size (In.)	Energy Input (Joules/in. $\times 10^{-3}$)	Temperature below which Cooling Rate will be Affected (deg. C.)
$\frac{1}{2}$	10	$\frac{3}{16}$	18	185
	8	$\frac{1}{4}$	25	265
$\frac{1}{4}$	10	$\frac{1}{8}$	11	280

With reference to point (*d*) the various conditions of heat-flow which can occur in practice should first be considered, and for this reason a few simple examples are shown in Fig. 24. The condition of unithermal* flow is not likely to be found in practice. Bithermal flow occurs in butt welds and trithermal flow in the majority of fillet welds. More severe conditions of heat flow are also shown in Fig. 24, namely, quadrithermal and quinquethermal, but these two types of flow are not very common. The best compromise for a weldability test is that it should give conditions equivalent to the most common butt and fillet joints, and the conditions necessary to satisfy this requirement are bithermal and trithermal flow. The length of each path available for heat flow is also important and this is linked with the previous discussion on total size of heat-sink, the ideal condition being obtained when all the path lengths are equal to or greater than 3 in.

* Heat flow through the equivalent of one plate section.

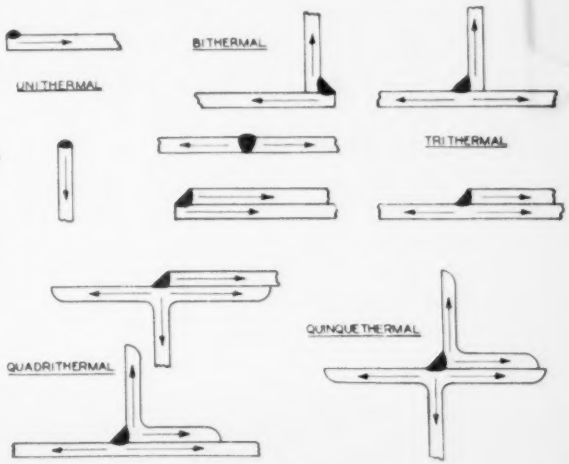
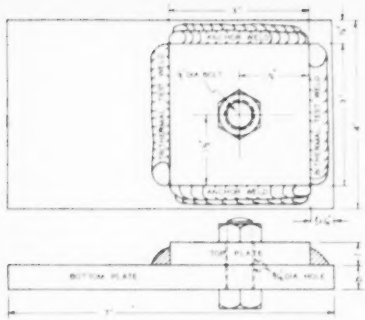


Fig. 24. Heat flow conditions related to joint geometry.



l = leg length of test weld. *t* = top plate thickness.
b = bottom plate thickness.

Fig. 25. C.T.S. weldability test assembly for low-alloy steel.

Having considered in detail all the relevant points in the design of a weldability test for high-tensile steel, it is now possible to specify the ideal test which, because it is based on heat flow, is termed the C.T.S. (Controlled Thermal Severity) Test. Since it is to be a restrained test the most simple form comprises two plates with a single clamping bolt. In order to obtain substantially equal path-lengths in the trithermal test the bottom plate should be at least twice as long as the top plate and, for simplicity the top plate should be square. A 3-in. square top plate on a 4 by 7 in. bottom plate meets these requirements and gives an adequate length of test weld. In addition, the heat sink volume is $37t$ cub. in., which is greater than the minimum requirement of $36\frac{1}{2}t$ cub. in. Fig. 25 shows how the top plate is placed near to one end of the bottom plate and restraining welds are made along two opposite sides of the top plate. The bithermal test-weld is made along the top plate edge adjacent to the end of the bottom plate and a trithermal weld along the opposite edge of the top plate. Both trithermal and bithermal test-welds can be made on one assembly provided that it is allowed to cool to room temperature between tests.

The results of experiments made on the C.T.S. test will be described in Part III of this investigation, and an evaluation of thermal severity will be made for the test using various plate thicknesses.

CONCLUSIONS

1. The initiation of hard-zone cracks in arc-welded joints in a manganese-molybdenum steel has been related to the cooling rate at 300 deg. C. in that zone when welding is carried out with B.E.A.M.A.-I.O.W. class E.217 electrodes. Welding of the steel was satisfactory provided that the cooling rate at 300 deg. C. in the hard zone did not exceed 6 deg. C. per sec.

2. When class E.317 electrodes were used to weld the same steel, cooling rates up to 9 deg. C. per sec. at 300 deg. C. in the hard zone gave crack-free joints.

3. With class E.645 low-hydrogen electrodes, crack-free joints have been obtained in the steel with cooling rates at 300 deg. C. up to 11 deg. C. per sec. in the hard zone.

4. From the above conclusions it appears that the cooling rate in the temperature range around 300 deg. C. is an important factor in the determination of the weldability of a manganese-molybdenum steel using class E.217, E.317 and E.645 electrodes. Because of this factor it is necessary for a weldability test to give rates of cooling at 300 deg. C. which are similar to those occurring in structural joints on plates of the same thickness.

5. It has been shown that the miniature Reeve test does not give rates of cooling as high as those obtaining in the majority of structural fillet welds, this effect being due to different heat-flow conditions. In the miniature Reeve test the heat sink is too small and heat-flow is essentially bithermal, whereas in most structural joints the flow is trithermal.

6. A weldability test has been described which gives trithermal flow. This test is called the unrestrained fillet test, and gives cooling rates and cracking results comparable to those obtained in a structure. It has been shown by comparing this test with the miniature Reeve test that, when using class E.217 electrodes on a manganese-molybdenum steel, external applied restraint plays, at most, a minor part in the initiation of hard-zone cracks, the important factor being rate of cooling.

7. The design of a new weldability test, based on heat-flow conditions which have been observed in this investigation, has been discussed. This test is of the restrained fillet type and two different conditions of heat flow, bithermal and trithermal, are obtained on one assembly. The test is called the B.W.R.A. Controlled Thermal Severity (C.T.S.) Test.

ACKNOWLEDGMENTS

The authors are indebted to the British Welding Research Association for permission to publish this report. Thanks are also due for valuable discussion of the work by members of the FM.8 Committee of the British Welding Research Association and the High Tensile Weldable Structural Steel Investigation Steering Committee of the Ministry of Supply who jointly guided the investigation.

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R.80

WELD HARDENABILITY OF CHROMIUM-MOLYBDENUM STEEL PIPE

This work was undertaken for the WEE/21/4 Committee of the British Standards Institution.

SYNOPSIS

Metal-arc welded samples of 1 per cent. chromium, ½ per cent. molybdenum steel pipe differing in wall thickness were provided by three different firms, using various sizes of electrode and preheating temperature. The lowest hardness in the heat-affected zone was associated with the highest temperature of preheat (300 deg. C.), and the results obtained indicate that a preheating temperature of not less than 200 deg. C. should be used when welding these steels.

INTRODUCTION

Differing opinions, reflected in practice, have been expressed as to the necessity or otherwise of preheating all sizes of pipe of the 1 per cent. Cr, ½ per cent. Mo steel composition prior to making butt-welds and also concerning the appropriate temperature to be used. It has been said that preheating of thin-walled tubing is unnecessary and that even for thicker walled material, preheating temperatures slightly in excess of 100 deg. C. should be adequate. However, it is the standard practice with many firms to use a preheating temperature of 300 deg. C., or above, for all thicknesses of tubing.

The committee decided that a research programme should be initiated to clear up the controversy and it was afterwards agreed that the results of the experimental observations should be published. In order to limit the scope of the investigations, hardenability was chosen as the criterion. This has served as a useful guide to the effect of preheating, though it is realised that the presence or otherwise of cracking anywhere in the welded joint would normally be the final arbiter.

DETAILS OF WELDED SAMPLES

The analyses for the pipe material used are given in Table I below:

Table I.—Analyses of Pipe Material

	(i) Samples from Babcock & Wilcox, Ltd.	(ii) Samples from Aiton & Co. Ltd.	(iii) Samples from Stewarts and Lloyds Ltd.
Carbon	0·14	0·14	0·13
Manganese	0·40	0·53	0·42
Silicon	0·25	0·12	0·224
Sulphur	0·026	0·017	0·043
Phosphorus	0·025	0·021	0·033
Chromium	0·77	0·88	0·73
Molybdenum	0·53	0·60	0·52
Nickel	0·15	0·29	0·09
Copper	—	—	0·15

The electrodes used for all the tests deposited metal containing approximately 0·5 per cent. molybdenum. The electrodes used by the first and second firms were to B.S. classification E.317 and those used by the third firm were to B.S. classification E.110P.

(a) Babcock & Wilcox Samples

These consisted of four samples of pipe of 1 in. wall thickness, on each of which beads 3 in. in length had been deposited from 10, 8 and 6 gauge electrodes.

Specimen A had been welded without preheating.

Specimen B had been welded after preheating to 100 deg. C.

Specimen C had been welded after preheating to 200 deg. C.

Specimen D had been welded after preheating to 300 deg. C.

All specimens were welded, using D.C., with the electrode positive. The welding current was 115 amps. for the 10-gauge rod, 140 amps. for the 8-gauge, and 200 amps for the 6-gauge.

The original pipe was cut in two positions after welding to give one cross-section at ¼ in. from the start of the welds and another at 1¼ in. from the start.

(b) Aiton & Co. Samples

These consisted of twelve samples of pipe of ⅝ in. thickness. On four samples a bead 3 in. in length had been deposited from 10-gauge electrodes; on another four samples a 3-in. bead from 8-gauge electrodes had been deposited, and on the remaining four a bead 3 in. in length from 6-gauge electrodes.

One bead from each gauge had been deposited without pre-heating (Specimen A, 10-gauge; Specimen B, 8-gauge; and Specimen C, 6-gauge). One bead from each gauge had been deposited after preheating to 100 deg. C. (Specimen D, 10-gauge; E, 8-gauge; and F, 6-gauge), and one bead from each gauge after preheating to 200 deg. C. (Specimen G, 10-gauge; H, 8-gauge; and I, 6-gauge), and one bead from each gauge after preheating to 300 deg. C. (Specimen J, 10-gauge; K, 8-gauge; and L, 6-gauge).

All the specimens were welded, using D.C., with the electrode negative. The welding current was 105 amps. for the 10-gauge, 134-140 amps. for the 8-gauge, and 180 amps. for the 6-gauge.

The original pipe was cut in two positions after welding to give one cross-section at ¼ in. from the start of the welds and another at 1¼ in. from the start.

(c) Stewarts and Lloyds Samples

These consisted of eight samples of pipe of 1 in. wall

thickness, on four of which had been deposited a bead 3 in. in length from 3/32 in. electrodes, and on the other four a bead 3 in. in length from $\frac{1}{8}$ in. electrodes. One bead from each size had been deposited without preheating, one from each size after preheating to 100 deg. C., one from each after preheating to 200 deg. C., and one from each after preheating to 300 deg. C.

All the specimens were welded, using D.C., with the electrode positive. The welding current was 130 amps. for the 5/32 in. diameter and 110 amps. for the $\frac{1}{8}$ in. diameter.

The original pipe was cut after welding to give one cross-section at $\frac{1}{4}$ in. from the start of the welds and another at $1\frac{1}{2}$ in. from the start.

DESCRIPTION OF INVESTIGATION

Preparation of samples.—Both faces of each of the specimens were very lightly ground, using a cut of 0·002 in. thickness, the specimens being kept cool during grinding. The ground faces were then polished on progressively finer emery papers down to Grade 500. This was followed by etching in 5 per cent. nital at 16 deg. C. for 30 secs.

Method of Testing.—Vickers Pyramid Hardness surveys were carried out across both cross-sections of each specimen, the load used being 10 kgm.

Photomacrographs of each cross-section were taken, showing all the hardness impressions and their respective V.P.H. numbers. Table II shows the values obtained for the hardest spot found in each fusion zone and in each weld metal deposit.

The Relation between Hardness and Preheating Temperatures

The results are given in Table II and show in general a progressive decline in hardness with increasing preheating temperature. Illustrations are available* for the whole series of tests made, but those reproduced in the report (Figs. 1-4) may be taken as typical.

Results from Babcock & Wilcox Samples.—It would appear that the preheating of these samples at 100 deg. C. had a detrimental effect on the fusion zones near to the start of the welds, though little effect at a distance of $1\frac{1}{4}$ in. from the start. The preheating to 200 deg. C. caused a marked reduction of hardness in the fusion zones, and the preheating to 300 deg. C. made a further improvement to the 6-gauge and 10-gauge samples but had no effect on the 8-gauge sample.

Results from Aiton & Co. Samples.—All the samples preheated to 100 deg. C. showed a definite reduction in fusion-zone hardness compared with the samples not preheated. The samples preheated to 200 deg. C. showed a marked decrease in fusion-zone hardness on the 10-gauge, a small decrease on the 8-gauge, but no decrease on the 6-gauge. The samples preheated to 300 deg. C. showed a further decrease in fusion-zone hardness on all gauges.

Results from Stewarts and Lloyds Samples.—The sample preheated to 100 deg. C. showed a definite reduction in fusion-zone hardness as compared with the samples not preheated. Preheating to 200 deg. C. and 300 deg. C. resulted in a progressive fall in the maximum fusion-zone hardness of both gauges.

* Copies of the illustrations can be obtained on loan on application to the Publications Officer, British Welding Research Association, 29, Park Crescent, W.1.

Table II

Electrode* Gauge (s.w.g.)	Pre-heating (Degrees Centigrade)	Position of Micro-Specimen from Start of weld	1 in. Wall Thickness — Babcock & Wilcox			$\frac{3}{4}$ in. Wall Thickness — Aiton & Co.			1 in. Wall Thickness — Stewarts & Lloyds		
			Code	Highest V.P.H. in Heat Affected Zone	Highest V.P.H. in Weld Metal	Code	Highest V.P.H. in Heat Affected Zone	Highest V.P.H. in Weld Metal	Code	Highest V.P.H. in Heat Affected Zone	Highest V.P.H. in Weld Metal
6	No pre-heat	At start of weld	AX.6	325	238	C.6	363	264	—	—	—
6	..	$1\frac{1}{4}$ & $1\frac{1}{2}$ in.	AY.6	325	249	C.6	336	253	—	—	—
6	100	$\frac{1}{4}$ in.	BX.6	327	238	F.6	317	247	—	—	—
6	100	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	BY.6	285	218	F.6	319	236	—	—	—
6	200	$\frac{1}{4}$ in.	CX.6	289	236	I.6	319	258	—	—	—
6	200	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	CY.6	270	228	I.6	319	254	—	—	—
6	300	$\frac{1}{4}$ in.	DX.6	264	215	L.6	268	238	—	—	—
6	300	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	DY.6	258	219	L.6	268	245	—	—	—
8 & $\frac{5}{32}$ in.	No pre-heat	$\frac{1}{4}$ in.	AX.8	306	236	B.8	376	294	$\frac{5}{32}$ in.	319	251
8 & $\frac{5}{32}$ in.	..	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	AY.8	339	260	B.8	390	302	$\frac{5}{32}$ in.	336	260
8 & $\frac{5}{32}$ in.	100	$\frac{1}{4}$ in.	BX.8	336	270	E.8	351	283	$\frac{5}{32}$ in.	283	236
8 & $\frac{5}{32}$ in.	100	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	BY.8	327	258	E.8	336	268	$\frac{5}{32}$ in.	304	236
8 & $\frac{5}{32}$ in.	200	$\frac{1}{4}$ in.	CX.8	285	228	H.8	333	279	$\frac{5}{32}$ in.	266	218
8 & $\frac{5}{32}$ in.	200	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	CY.8	260	219	H.8	345	274	$\frac{5}{32}$ in.	253	215
8 & $\frac{5}{32}$ in.	300	$\frac{1}{4}$ in.	DX.8	281	243	K.8	274	236	$\frac{5}{32}$ in.	243	218
8 & $\frac{5}{32}$ in.	300	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	DY.8	262	274	K.8	285	236	$\frac{5}{32}$ in.	247	215
10 & $\frac{1}{8}$ in.	No pre-heat	$\frac{1}{4}$ in.	AX.10	299	225	A.10	409	345	$\frac{1}{8}$ in.	363	270
10 & $\frac{1}{8}$ in.	..	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	AY.10	354	260	A.10	394	354	$\frac{1}{8}$ in.	363	292
10 & $\frac{1}{8}$ in.	100	$\frac{1}{4}$ in.	BX.10	330	218	D.10	370	287	$\frac{1}{8}$ in.	304	247
10 & $\frac{1}{8}$ in.	100	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	BY.10	333	245	D.10	363	299	$\frac{1}{8}$ in.	309	256
10 & $\frac{1}{8}$ in.	200	$\frac{1}{4}$ in.	CX.10	297	215	G.10	348	256	$\frac{1}{8}$ in.	264	219
10 & $\frac{1}{8}$ in.	200	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	CY.10	274	236	G.10	357	262	$\frac{1}{8}$ in.	283	228
10 & $\frac{1}{8}$ in.	300	$\frac{1}{4}$ in.	DX.10	281	236	J.10	285	222	$\frac{1}{8}$ in.	266	232
10 & $\frac{1}{8}$ in.	300	$1\frac{1}{4}$ in. & $1\frac{1}{2}$ in.	DY.10	253	238	J.10	299	238	$\frac{1}{8}$ in.	260	222

* The electrode sizes given in this column as fractions of an inch refer to Stewarts & Lloyds samples only.

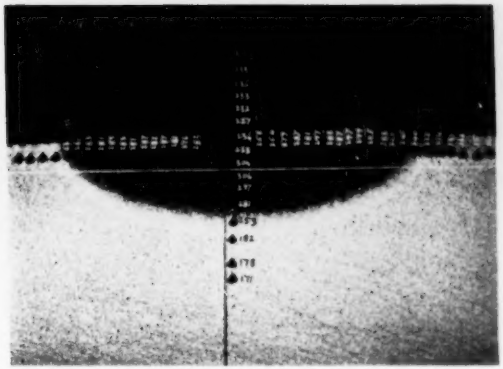

Fig. 1. *Babcock & Wilcox*—No preheat. ¼ in. from start of weld.

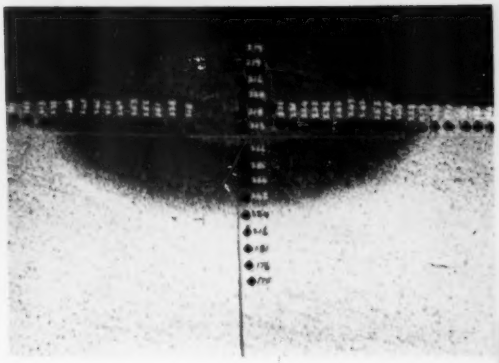

Fig. 3. *Babcock & Wilcox*—200 deg. C. preheat. ¼ in. from start of weld.

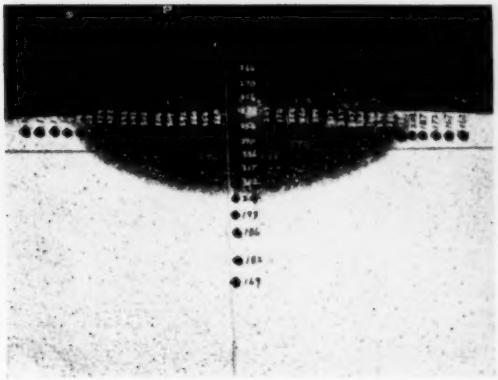

Fig. 2. *Babcock & Wilcox*—100 deg. C. preheat. ¼ in. from start of weld.

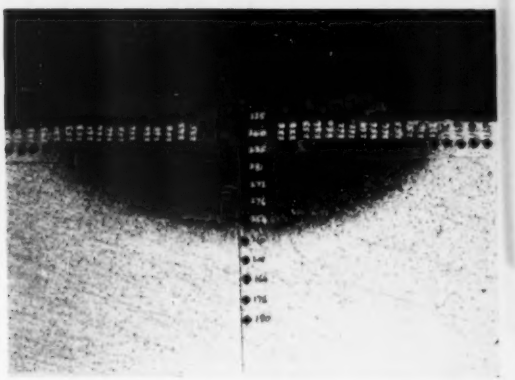

Fig. 4. *Babcock & Wilcox*—300 deg. C. preheat. ¼ in. from start of weld.

Summary of Results obtained from all the Samples Submitted.

The hardness figures obtained from the samples welded by Messrs. Babcock & Wilcox without preheating were very similar for each gauge and all showed a progressive reduction of the maximum fusion-zone hardness with increase of preheating temperature, except for the 100 deg. C. preheat which had a detrimental effect on the start of the welds.

The samples welded by Messrs. Aiton & Co. without preheating were considerably harder in the fusion zone than any of the other samples submitted for test, and the hardness increased with a decrease in electrode size, the values for 10-gauge electrodes being the highest. There was, however, a distinct reduction in hardness of the fusion zone as a result of preheating to 100 deg. C., but this did not occur in the Babcock and Wilcox samples. Once again a progressive

reduction of the maximum fusion-zone hardness with increase of preheating temperature was shown. The hardness was not reduced to the values obtained for the Babcock & Wilcox samples at the centre of the welds, however, even by preheating to 300 deg. C.

The maximum fusion-zone hardness of the samples welded by Messrs. Stewarts and Lloyds using 5/32 in. diameter electrodes without preheating was similar to that obtained from 8-gauge Babcock & Wilcox samples. Their $\frac{1}{4}$ in. samples were much harder than the 10-gauge Babcock & Wilcox samples, although softer than the corresponding samples from Aiton & Co. No samples were submitted by Messrs. Stewarts and Lloyds comparable with the 6-gauge samples submitted by other firms.

As before, the samples from Stewarts and Lloyds showed reduction of maximum fusion-zone hardness with increase of preheating temperature, although the smaller gauge sample was less susceptible to this reduction than the larger gauge, even with preheating to 300 deg. C.

CONCLUSIONS

1. From the results of this series of tests it is apparent that the best results are achieved by preheating to 300 deg. C., although a marked reduction in fusion-zone hardness can be obtained by preheating to 200 deg. C.

2. On the basis of these tests, the B.S.I. Committee preparing the draft British Standard for the metal-arc welding of high temperature and high pressure pipe lines decided to recommend that a minimum preheating temperature of 200 deg. C. should be specified for the welding of 1 per cent. chromium, $\frac{1}{2}$ per cent. molybdenum steel pipe material.

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